STANDARDIZED, LOW COST COMMUNICATIONS FOR PLANETARY MISSIONS[1]

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Abstract

For Deep Space Missions, the Radio-frequency (RF) communications link provides both communications and navigation services. In this article we discuss the increased efficiency and reduced cosf that can result from the potential consolidation of the two services info one suite of equipment, and the utilization of "guaranteed delivery" standard pro tocols to improve the communications service.

In recent years, JPL has developed and deployed the Block V Receiver (BVR) and the Block V Exciter (B VE). The B VR is a highly-accurate. digital receiver that recovers telemetry at rates as high as 26 Msym/s and provides interim products needed for navigation (ranging and Doppler). The B VE generates highly-stable S-, X-, and Ka-band signals with carrier, command and ranging components. The BVR and B VE can serve as the building blocks in this proposed consolidated uplink/downlink processing system. I-he architecture is especially suitable for the support of Mars exploration, when it is desired to support multiple objects that are present in the same antenna beam, with a single antenna.

The proposed implementation provides the environment for embedding TCP/IP-like protocols for telemetry/command, with automatic acknowledgment and retransmission. It is envisioned that spacecraft will buffer science dafa and transmit it with full acknowledgment (and needed retransmission) from the ground system. In a similar way, the spacecraft will acknowledge receipt of commands, otherwise commands will be automatically resent. This protocol is consistent with the thrust for more autonomous spacecraft - it will eliminate the manual process of validating the success of transmissions and scheduling refransmissions, and increase the reliability of the communications service.

1. <u>INTRODUCTION</u>

The RF link between Earth and a planetary mission provides both a communications service and a navigation service. The communications service consists of uplinking commands to the spacecraft and downlinking science and status telemetry. The Navigation service estimates spacecraft trajectory from the uplink/downlink RF signals primarily via the measurement of the ranging code(s) and the Doppler frequency and rate.

Could these services be fulfilled using Earth-orbiter support equipment? Unlike planetary missions, Earth-

[1] The **work reported in this paper was performed at the Jet Propulsion Laboratory, California Institute of** Technology, under the sponsorship of the **National Aeronautics and Space Administration.**

orbiters usually use the RF link only for communications - navigation is derived from the Global Positioning System (GPS) or through other means. The special stability and sensitivity required for Deep Space navigation (and for some Deep Space communications with weak-signal missions), is usually not required of, or designed into, equipment that is designed primarily to support Earth orbiters.

The Jet Propulsion Laboratory (JPL) has been providing communications and navigation services for planetary missions via its Deep Space Network (DSN). Recently, the DSN has deployed a new generation of all-digital receivers (Block V Receivers, or BVR's) that provide most of the downlink functions of the communications service and support the navigation services. A new generation of Exciters (Block V Exciters or EWE'S) are being deployed at present and will support key aspects of the uplink portion of the services. The BVR and BVE serve as the core of a proposed consolidated signal processing system that can reduce the cost of routine operation and enable closer involvement by the mission's scientists. In this paper we review the architecture of the communications and navigation services for single antenna and multiple antenna configurations (Section 2), provide overview of the BVR and BVE (Section 3), then show how BVR and BVE can be extended to a consolidated equipment suite, to meet the need for cost-effective communications and navigation services. (Section 4).

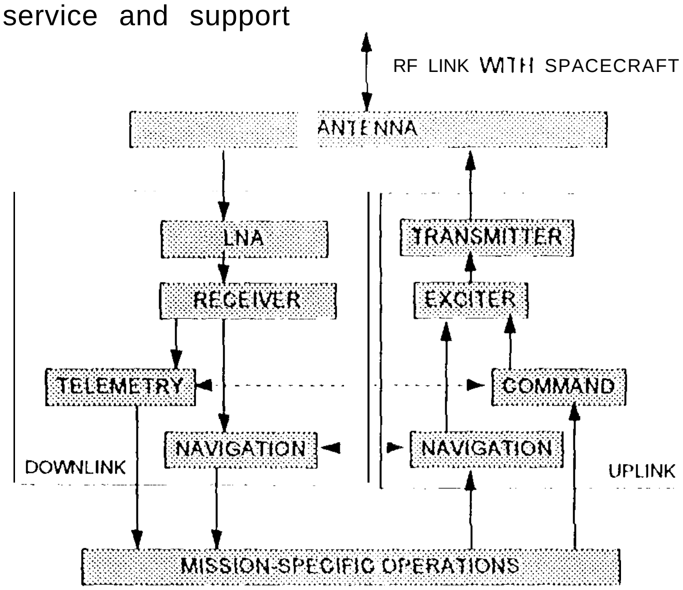

Figure 1- Spacecraft Ground Support - Functional Block Diagram

2. COMMUNICATIONS AND NAVIGATION

Figure 1 shows the single-antenna configuration for communications and navigation. On the uplink side, command and ranging code that were requested by the project are generated as baseband signals and are modulated on an RF carrier. The RF carrier may be at a fixed frequency or swept to enable signal acquisition by tile spacecraft. Note that unlike near-earth spacecraft, the acknowledgment of successful uplink will take at least a round-trip-light-time (RTLT) which is often over an hour.

On the downlink side, the RF signal received at the antenna, is collected by a low-noise amplifier (LNA) and sent to a receiver which tracks and removes the carrier component. Then, a telemetry processor recovers the telemetry frames and. a navigation processor recovers the required products, usually Doppler and ranging.

Figure 1 also indicates two feedback paths, one for the communications service and one for the navigation service. The feedback path between the command and telemetry functions provides acknowledgment that commands were received by the spacecraft and downlinked data were received by the project. While at present this acknowledgment (and retransmission) service is usually manual, there are benefits in embedding it in the protocol, in a manner similar to the TCP/IP implementation, making it transparent to the user.

Navigation is derived from measurements of the range to the spacecraft and its Doppler signature. Both measurements require uplink and downlink. Typically, a ranging code and a Doppler reference are transmitted to the spacecraft, where a transponder simply echoes them to Earth, with a simple frequency translation. The navigation observable are the range, phase and frequency differences between the transmitted reference and the received signal - spacecraft trajectory is estimated from these observables.

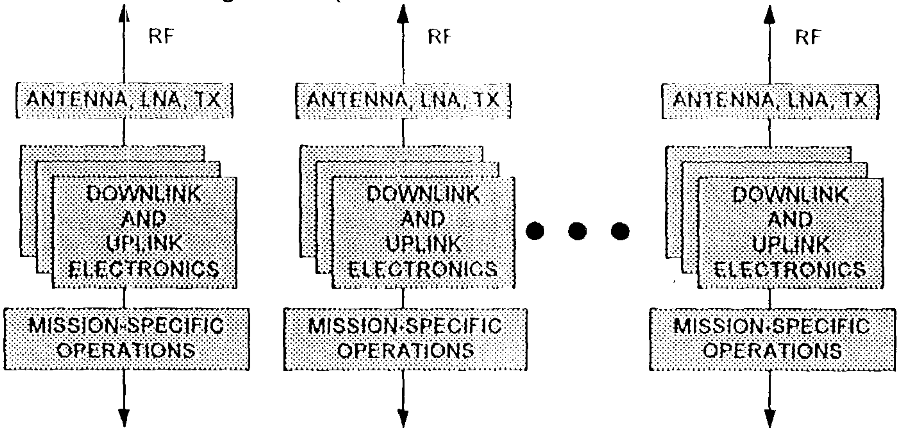

Figure 2- DSN Architecture, Option A - Dedicated Links

Next, we need to evaluate candidate architectures for the multiple-antenna environment of the DSN. For planetary mission support environment, the communications and navigation services are affected by three additional factors:

2.1 The DSN has multiple antennas at a single site. At present the DSN operates three DSCCS (Deep Space Communications Complexes): GDSCC at Goldstone, California; CDSCC, near Canberra, Australia; and MDSCC, near Madrid, Spain. Each DSCC supports Deep Space missions with a 70-meter antenna and several 34-meter antennas (the DSCC have additional smaller antennas that support near-earth missions).

The architecture must provide for cost-effective equipment redundancy.

2.2 Unlike near-Earth missions, Deep Space missions may use uplink and downlink from different antennas, indeed from antennas at different DSCCs. This is because the large RTLT introduces a large offset between the uplink coverage and downlink coverage. Indeed DSN communications and navigation are conducted in three modes: l-way (no uplink is present), 2-way (uplink is transmitted from the same antenna that receives the downlink), and 3-way (uplink and downlink are provided by different antennas). As we discuss later, the feedback paths between uplink and downlink can be implemented via low-rate messages between the ground antennas thus 3-way operation is not inherently limited to antennas in the same DSCC.

2.3 For Deep Space missions, it is required at times to array the downlink signals from multiple antennas, primarily to increase the effective G/T (ratio of Antenna Gain to System Noise Temperature)

Figures 2, 3 and 4 show three candidate architectures. This list is not exhaustive but serves to indicate the range of options. Note that since the transmitter and the LNA must be physically mounted as part of the antenna, we show them as part of the antenna functional block.

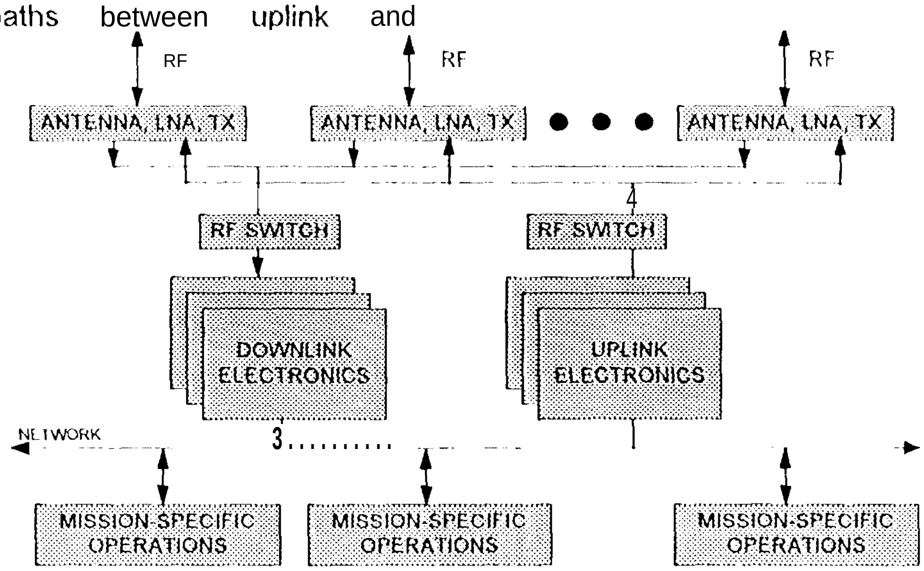

Figure 3- DSN Architecture, option B - Switched Consolidated Electronics

The architecture shown in Figure 2 has a single electronic suite that performs both the uplink and the downlink functions. Several copies of this suite are attached to an antenna, as many as required to meet link availability. There is no physical switching whatsoever, though that there **is the switching inherent in the use of a** network. In terms of hardware, this architecture uses the most equipment - each antenna has dedicated redundant equipment. However, the lack of switches reduces the dependency between missions. In terms of service, once a user has an antenna assigned to provide the required service, all the ancillary equipment is immediately available, independent of the other missions.

In the architecture depicted in Figure 3, the uplink electronics are consolidated into one suite and the downlink electronics are consolidated into a second suite. Multiple suites of uplink and downlink electronics are provided, sufficient to support all the antennas and meet the aggregate availability requirement, RF switches provide the routing between the antennas and the electronic suites. This architecture requires less electronics equipment than option A, but introduces a modest amount of coupling between missions.

Finally, in Figure 4 we show an architecture with the most flexibility. Functions are implemented separately and links are assembled as needed from the available components.

Before assessing how the three architectures meet the DSN needs, let us review the DSN'S present architecture. The DSN was started in the ' early 1960 and upgraded as technology advancements, mission requirements, and budget constraints dictated. In the 60's and 70's, technology forced the implementation of the functions of Figure 1 in separate assemblies, namely receivers, telemetry, ranging, Doppler, etc. I-he high cost of the equipment restricted the number of units, thus the resulting architecture evolved into a variation on Option C - a large number of assemblies with switches or patch panels between them. The assemblies are treated as a large pool - individual assemblies are assembled into a link to support a mission, then at the end of the support, the link is dissolved and the assemblies are released to the assembly pool. This "assembly pool" and "link forming/dissolution" approach is the basis to the DSN'S operations concept. Though at present much of the switching and link forming/dissolution are manual, the DSN can be upgraded to Option C with minor changes in the operational concepts. Changing the DSN to meet architectures A or B will require a significant change in the operational concept

Let us reflect on the role of switches. Extensive use of switches, such as that proposed by Option C, can result in significant reduction in the amount of hardware and effective utilization of the installed hardware. However, switches represent a single point-of-failure for the whole DSCC and must be designed for extremely high reliability, redundancy and automation. As advances in digital technology drastically cut the cost of replication, Options B and C will become more attractive.

How about arraying? Options B and C can be easily adapted for arraying: the combined RF signal from multiple antennas is re-injected into the RF switch and processed through the same downlink electronics as the RF signal from a single antenna. Arraying with Option A required some mechanism for cross-strapping the signal between antennas.

Options B and C are best suited to support the Mars missions, where multiple object are present in the same antenna beam. The RF switch allows the support of many objects with a single antenna.

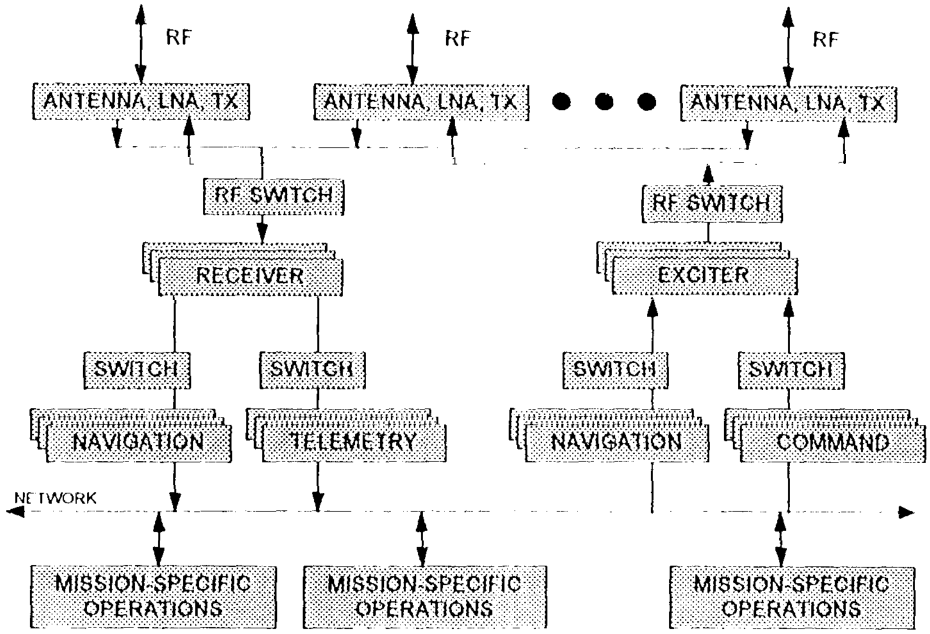

Figure 4- DSN Architecture, Option C - Switched assemblies

How is the navigation service provided in these architectures? As stated earlier, the navigator estimate the spacecraft trajectory from ranging and Doppler observable. The Doppler observable are the phase and frequency offsets between an uplink carrier and the frequency-translated downlink replica of this carrier. In the past, the uplink and downlink carriers were physically mixed together, the phase and frequency of the "beat" frequency were measured. This limited the Doppler measurement to uplink and downlink from antennas that are in physical proximity to each other. Today, with highly-accurate timing systems, the physical coupling between uplink and downlink is no longer needed. All the navigators need is a time-tagged record of the uplink frequency and a time-tagged record of the downlinked frequency. The two records may be derived on separate continents . as long as the DSCC's timing systems are locked to each other, these records are suitable to derive Doppler observable.

In a similar way, the ranging observable is the phase difference between an uplinked ranging code and the frequency-translated downlinked replica of that code. In the existing DSN equipment, there is a physical connection between the uplink ranging equipment and the downlink ranging equipment, With precise timing, the downlink station can generate a replica of the uplink ranging code, perform the required correlation, and provide the navigators with time-tagged ranging observable. In summary, the existing physical coupling between uplink and downlink is replaced by messages between the uplink and downlink, e.g. over a network, The messages are relatively few and are used just to coordinate the timing, i.e. the ramping of the carrier or the start of the ranging code.

While the current navigation service suffers from too much coupling between uplink and downlink, the communications service provides too little. 1 here is no automated mechanism to detect loss-of-data and request retransmission, neither in the downlinking of telemetry, nor in the uplinking of commands. This deficiency is addressed by providing CCSDS-level file transfer protocols. Note that for Deep Space support, the whole DSN is treated as a single communications node as due to large RTLT, uplink and downlink occur over different antennas, or even different DSCC's.

3. THE BVR AND BVE

1 he Block V Receiver (BVR) [2] was deployed at all the DSCCs in mid-1995. As shown in Figure 5, there is a downconversion from RF to IF at the antenna, then the IF signal is transported to the signal processing center (SPC) in a fiber-optic, over distances as long as 10 miles. At the SPC, the IF signal undergoes minimal conditioning, then is sampled at 160 MHz and processed digitally to produce soft telemetry symbols, Doppler measurements, and baseband data for ranging extraction. The BVR is based on three JPL-developed GaAs Application Specific Integrated Circuits (ASICs), each with more than 160,000 used gates that perform the carrier, subcarrier and symbol demodulation functions.

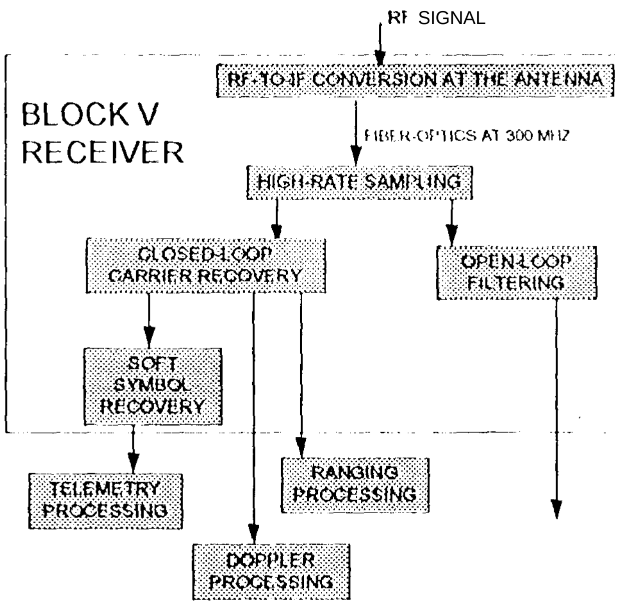

Figure 4- Block V Receiver - Functional Components

I-he emphasis in the BVR implementation is on achieving high stability while minimizing processing losses. Thus, while other "all-digital" receivers use 1- or 2-bit sampling and processing, the BVR uses 8-bit sampling and processing - use of 2-bit sampling introduces a loss as large as 0.5 dB compared to 8-bit sampling.

Similarly, the BVR sampling is at fixed rate. Other all-digital receivers sample the signal at a rate that is coherent to the telemetry rate. This simplifies telemetry processing but makes precision recovery of the ranging code very difficult.

With a clock rate of 160 Mhz, the BVR is specified to recover up to 13 Msym/s of BPSK telemetry or 26 MHz of QPSK telemetry. These are rates that are high enough to support all present and foreseeable planetary missions.

The BVE development was completed in late-1995 and the first unit was deployed at GDSCC - the remainder of the units are scheduled for deployment by 1998. The BVE, shown in Figure 6 uses al-digital techniques to create several high-fidelity carriers that are coherent with each other. This is a unique feature of Deep Space Missions where carriers at S-, X-, and Ka-band are often uplinked to the spacecraft at the same time, coherent with each other, to meet scientific or engineering goals. The all-digital signal generation is required both to create the high-accuracy programmable signal, and to control the level of spurious signals.

A measure of the required stability of the BVR and BVE is that to meet the navigation accuracy, the Doppler observable (uplink frequency minus downlink frequency) must have jitter no larger that 5 mHz RMS. with X-band communications at 8.1-8.4 MHz, the frequency stability and nettability of both the BVR and BVE are extremely tight and they are met in the fielded units.

At this point we should note an example of the interaction between technology and architecture. While for the BVR, an IF signals traverses the distance between the antenna and the SPC, in the BVE, an RF signal is sent over the fiber-optic. The improvement in the performance of fiber-optics over between the BVR design and BVE design eliminated the need to perform IF-to-RF upconversion at the antenna (at least for the S- and X-band signals), eliminating the difficult need to create a highly-stable upconversion reference signal at the antenna.

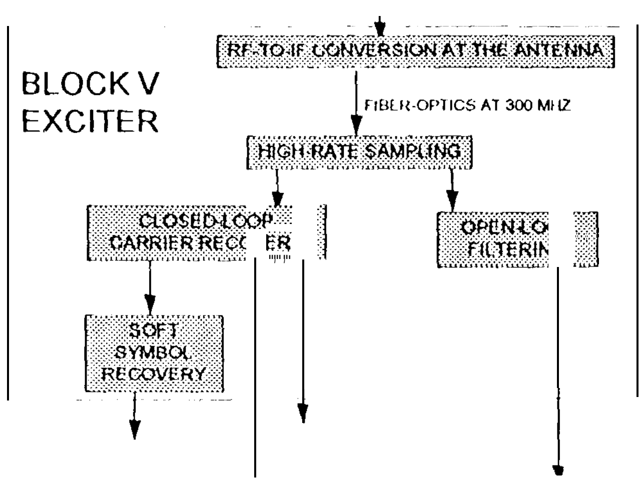

Figure 5 - Block V Exciter - Functional Components (NEED NEW PICTURE)

4. EQUIPMENT CONSOLIDATION

With the great strides in digital electronics over the last decade, consolidation of equipment as per Option B promises great reductions in the amount of equipment, simplification of maintenance, and streamlining of operations. A preliminary study has shown that the **DSN** rack count can be cut by 80 racks in the three DSCC's, reducing the rack count by more than 50%. Similar assessment of Options A and C will also be conducted.

With the BVR and BVE being at state-of-the-art, the consolidation focuses on packaging the other functions within the BVR/BVE, and then adding the system-level interfaces between the uplink and downlink. Specifically, the BVR is extended to single rack, Downlink Processor (DLP), that performs all the downconversion, receiving, telemetry and navigation functions. In a similar way, the BVE is extended to a single rack, Uplink Processor (ULP) that performs all the navigation, command, and exciter functions. As shown in Option B, enough copies of the DLP and ULP are present in each DSCC to support the existing antennas and arraying, with additional racks added to support maintenance and repair.

The DLP performs carrier recovery for both suppressed carrier and non-suppressed carrier signals. It recovers BPSK and QPSK telemetry both in direct modulation and residual carrier modes, at rates from 4 symbols/see to 26 MSym/s.

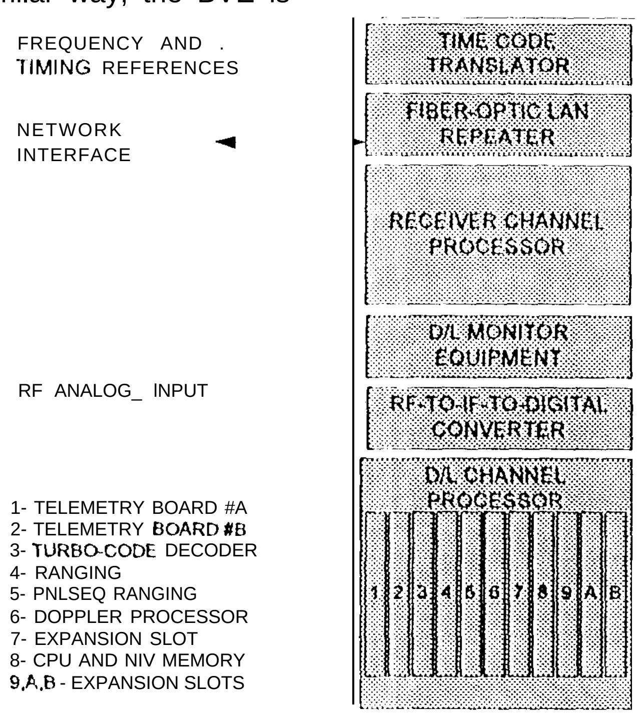

Figure 6- DLP Proposed Hardware Configuration

The DLP will have a frame-based decoder - frames are detected in the symbol domain, then time-tagged and buffered as annotated **data units** similar to the present SFDU units. These units are "sent" to the appropriate decoder for processing.

Because data capture occurs very early in the process, reliable communications and concurrent processing for this data in the subsequent stages is enabled. It also allows for the reverse recovery of the symbol stream when frame decoding and verification processes are used. It is very suitable for incremental implementation of high-speed decoders, e.g. build a I-Mbits/s Viterbi decoder for (15,1/6) convolutional code and then use several of these cards in parallel to achieve any desired higher rate. The architecture is also suitable for expansion to any future frame-based error-correcting codes. For example the recently discovered Turbo codes [3] will be decoded **by a** single-card decoder **in** the VME chassis.

The DLP provides for the recovery of the sequential as well as the pseudo-random ranging codes. The DLP output is a time-tagged Earth-arrival time of a marker in the ranging code that, combined with the time-tagged earth transmit time, can be converted to a range.

The DLP and the ULP could be operated in two modes: in the DSN-mode, the equipment is operated from a standard DSN console as part of a DSN link while in the Pi-mode the equipment is operated by an external P1. Though the interfaces and the displays may be significantly different, the equipment operation remains the same. The PI mode would be available primarily to experienced and knowledgeable PIs who are interested in taking direct control of the equipment while assuming at the same time responsibility for the results.

5. CONCLUSIONS

We have reviewed several options to upgrade the DSN communications and navigation services to the new era of many small interplanetary services, while taking advantage of the recently introduced BVR and BVE electronics.

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ACRONYMS

B VE	*Block V Exciter*
B VR	*Block V Receiver*
CCSDS	*Consultive Committee for Space Data Systems*
CDSCC	*Canberra DSCC*
DSCC	*Deep Space Communications Complex*
DSN	*Deep Space Network*
GDSCC	*Goldstone DSCC*
GPS	*Global Positioning System*
IF	*Intermidiate Frequency*
JPL	*Jef Propulsion Laboratory*
MDSCC	*Madrid DSCC*
RF	*Radio Frequency*